Monte Carlo Simulations of Light Scattering by Clouds

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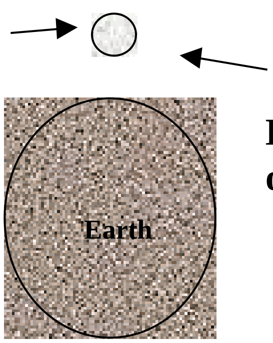
Abstract

We present Monte Carlo simulations of photon-transport in clouds, with emphasis on deducing the temporal structure of the emission from the structure of the scatter-delayed and -broadened observable pulse. The simulations are specifically designed to address the appearance and detection of lightning in satellite data. In the model, discrete photons are advanced by a standard time step through a distribution of water droplets with variable size and number density distribution. We use a Henyey-Greenstein phase function to approximate Mie scattering, and a single scattering albedo of $\omega_0 = 0.99996$. The model is capable of handling a variety of cloud/pulse geometries and arbitrary spatio-temporal pulse profiles, and of constructing the delayed/dispersed/attenuated light curve at any arbitrary point located at the satellite's altitude above the Earth. We compare previous models, our simplest case results and data from the FORTE satellite.

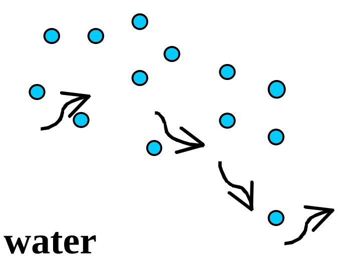
Cloud



1.

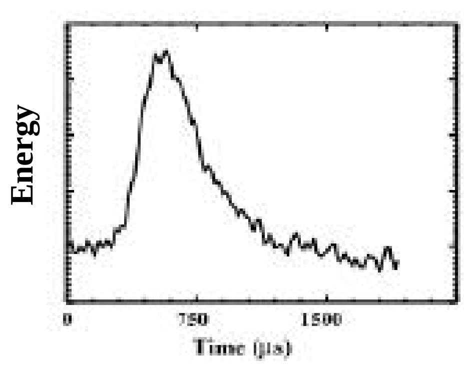
Event occurs, either inside or beneath cloud

2.



Light scatters off water droplets, causing a delay in escaping the cloud

3. Pulse that escapes is delayed and broadened by the scattering.



Question: what do the delay and width of the transmitted pulse tell us about the discharge and the intervening cloud?

The Model

- **Code is written using IDL.**

- **We use a Henyey-Greenstein phase function with *g* = *0.85*, corresponding to heavily forward-scattered light, that is, in most interactions the photon is only slightly deflected.**

- **Entire population of photons is treated simultaneously (**N_γ 10−15,000**).**

- **The code advances with a standard time step, corresponding to the smallest likely free path length; hence not every photon interacts with every time step.**

- **In any scattering event, the photon is simply re-directed with no loss of energy. Similarly, there are no "partial absorptions."**

- **In each interaction, there is a small but non-zero probability that the photon will be absorbed:** $P_{abs} = 1 - \omega_o$ **where** $\omega_o = 0.99996$ **for** *10*μ **water drops and NIR (**λ 0.87**) photons.**

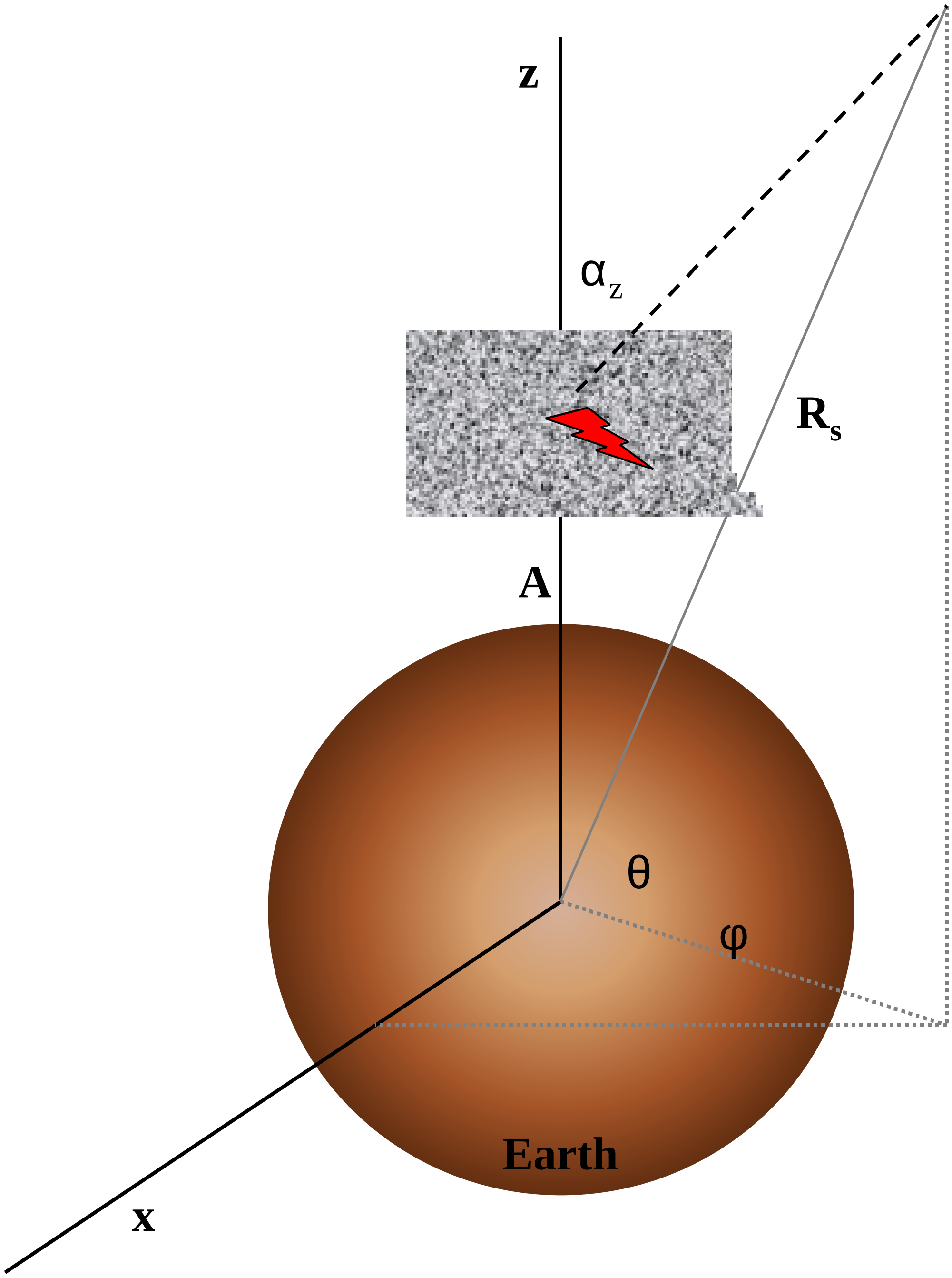
- **The coordinate system is Earth-centric, with the "sky" being the sphere at an altitude of 825 km.**

- **The event occurs somewhere either within or below cloud.**

- **We track the time at which each photons escaping the cloud reaches either the sky or the ground; the ground is taken to be perfectly absorbing.**

The Model

R_s = satellite radius = 7225 km
A = cloud altitude
α_z = zenith angle



The Model

What we want

- Detection rate/probability as a function of
  - — event's location relative to satellite and cloud
  - — event's integrated magnitude or peak intensity
  - — event type
- Can observed pulse (delay, width, structure) help discriminate
  - — event position within cloud?
  - — event type?

What we need

- Finite clouds of arbitrary shape
- Transient light sources
- Inhomogeneous clouds
- Variable viewing angle

Background

Scattering

- **Mie scattering is the correct, formal solution for large ($2\pi a/\lambda >> 1$) spherical scatterers, but requires solution for each size parameter of interest.**

•Parameters necessary to model scattering:

— **Phase function,** $p(\mu)$

— **Mean free path,** $\Lambda = 1/2\pi a^2 N$

— **Geometric cloud depth,** L

— **Optical depth of cloud,** $\tau = L/\Lambda$

- **"Henyey-Greenstein" = approximation to Mie scattering. Phase function:**

$$p(\mu) = \frac{1 - g^2}{(1 + g^2 - 2g\mu)^{3/2}}$$

where θ **is the scattering angle,** $\mu = \cos\theta$**, and** g **is the asymmetry factor,** $g = \mu$ **.**

- **In the limit of multiple scatterings (**$L/\Lambda >> 1$**), the problem becomes one of diffusion, for isotropic scattering.**
- **For non-isotropic case, we can use the diffusion relations if we re-define:**

$$\Lambda_d = \Lambda/(1-g)$$

$$\tau_d = L/\Lambda_d$$

Background

Diffusion

- **In diffusion, photon escapes cloud via a random walk, in which net displacement (*d*) scales as the *square root* of the travel time, and is proportional to the "diffusivity,"** $D = c\Lambda_d$**:**

$$d^2 = Dt$$

- **Thus the "scattering delay" is the time it would have taken for the photon to reach distance** L **in free air, compared to the time required via random walk:**

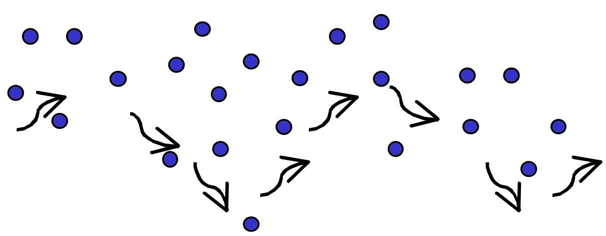
$$\Delta t_{delay} = L[\tau(1-g) - 1]/c$$

- **The total path length traveled in reaching distance L is:**

$$P = ct_L = cL^2/D = L^2/\Lambda_d$$

and therefore the average number of steps required is:

$$N_{steps} = P/\Lambda = (1-g)\tau^2$$



Background

Previous Studies

1. **Twomey '66**
2. **Danielson et al. '69**
3. **Hansen '71**
4. **Bucher '73**
5. **McKee & Cox '74**
6. **Thomason & Krider '82**
7. **Koshak et al '94**
8. **Davis et al. '96-'99**
9. **Brower '97**
10. **Pfeilsticker et al. '98**

- **NB: Not a complete list**
- **Both analytic and Monte Carlo studies**
- **Very few incorporate all of what we need to understand FORTE/PDD data, namely**
  - **— Finite clouds**
  - **— Transient source**
  - **— Time-series output**
- **References in red are the closest to this present study, and we use their results to validate our simplest case studies.**

Main findings:

— Diffused sunlight tells us little besides cloud optical depth. **[1]**

— Aerosols must be present to account for the degree of absorption seen in clouds. **[2]**

— Due to multiple scatterings, the throughput signal is largely insensitive to the cloud microstructure. **[3]**

— Losses from sides of cloud are significant. **[5]**

— Even thin cloud layers will prevent almost all the light produced below a thunderstorm from reaching a satellite. **[6]**

— Long geometric path lengths traveled insidethick clouds account for anomalously large reported absorption by atmospheric trace gasses. **[10]**

Results

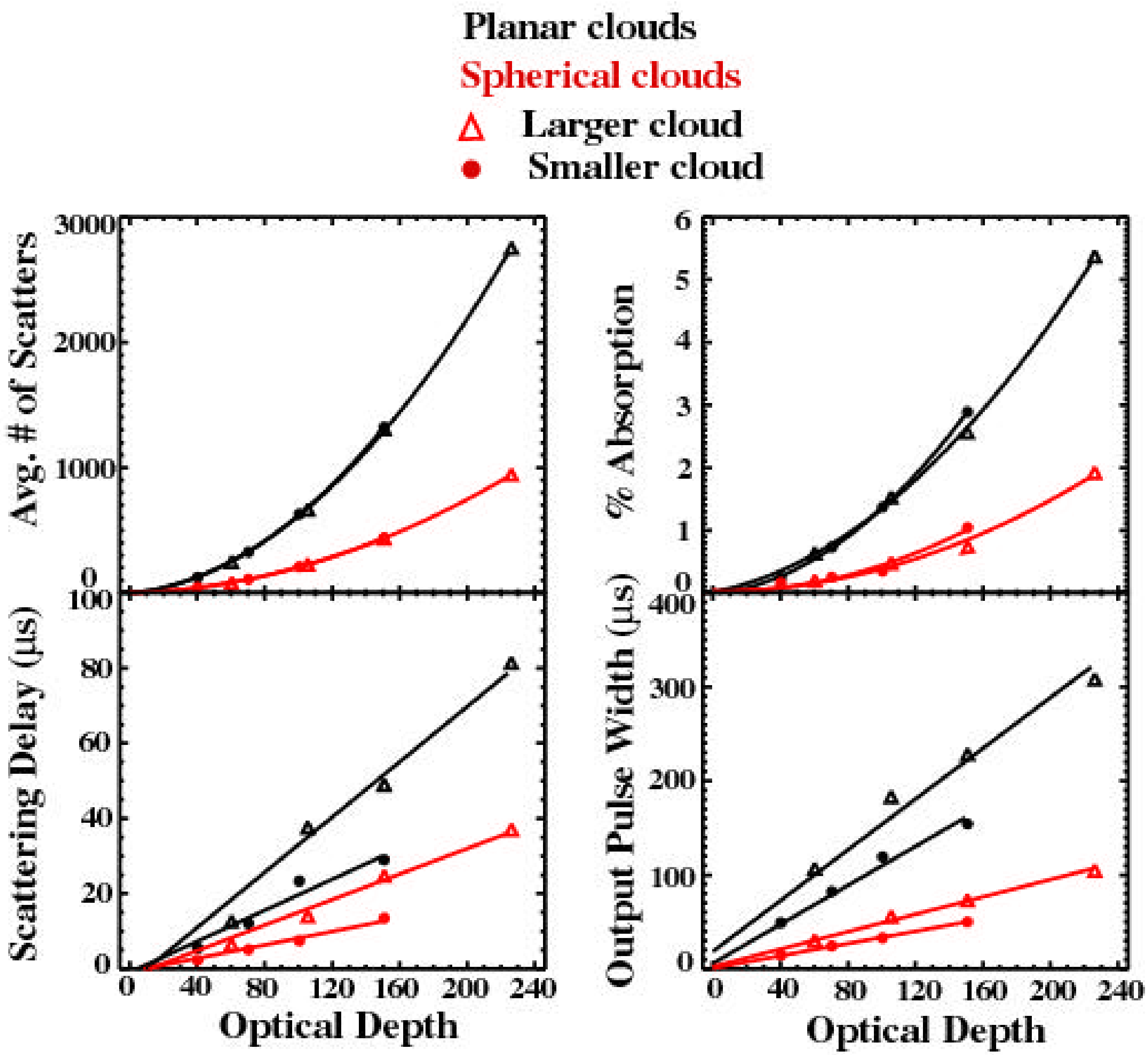
1. Impulse Response of the System

These panels show that the impulse response of the simulated system behaves as we expect on the basis of simple diffusion theory. That is, the number of interactions increases quadratically with the optical depth of the cloud, and the delay due to scattering of the output signal increases linearly both with the cloud optical and geometric depths. The absorption increases with the number of interactions, and the output signal temporal width increases with the delay.

Red lines indicate test cases run with spherical clouds, while black lines indicate planar clouds. These two shapes were chosen to represent the most extreme cases.

Dots indicate test cases using clouds of smaller geometric depth (size) and triangles indicate larger clouds.

(1)


Planar clouds
Spherical clouds
Larger cloud
Smaller cloud
Avg. # of Scatters
% Absorption
Scattering Delay (μs)
Output Pulse Width (μs)
Optical Depth
Optical Depth

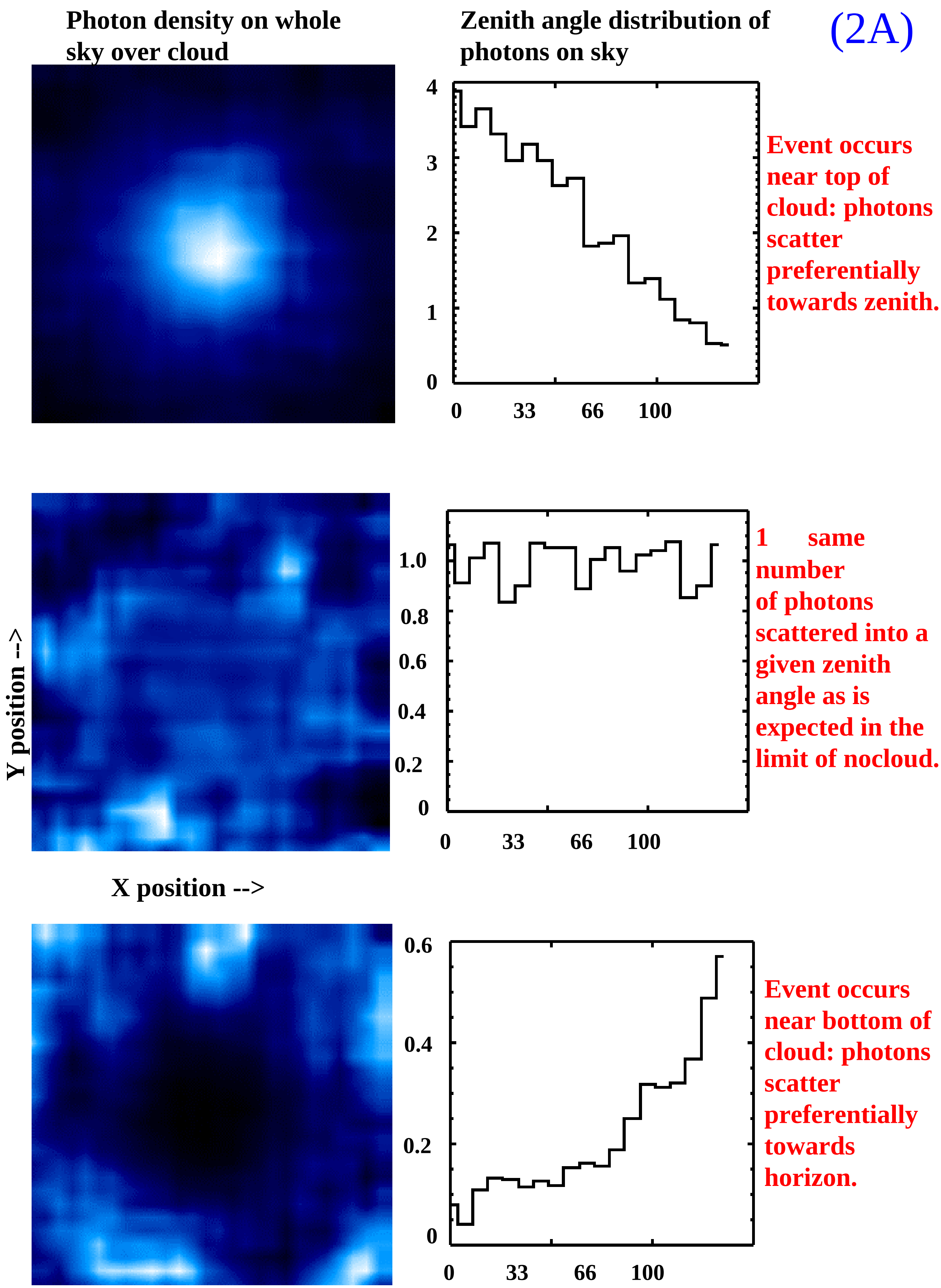
Results

2. Event Position Within Cloud

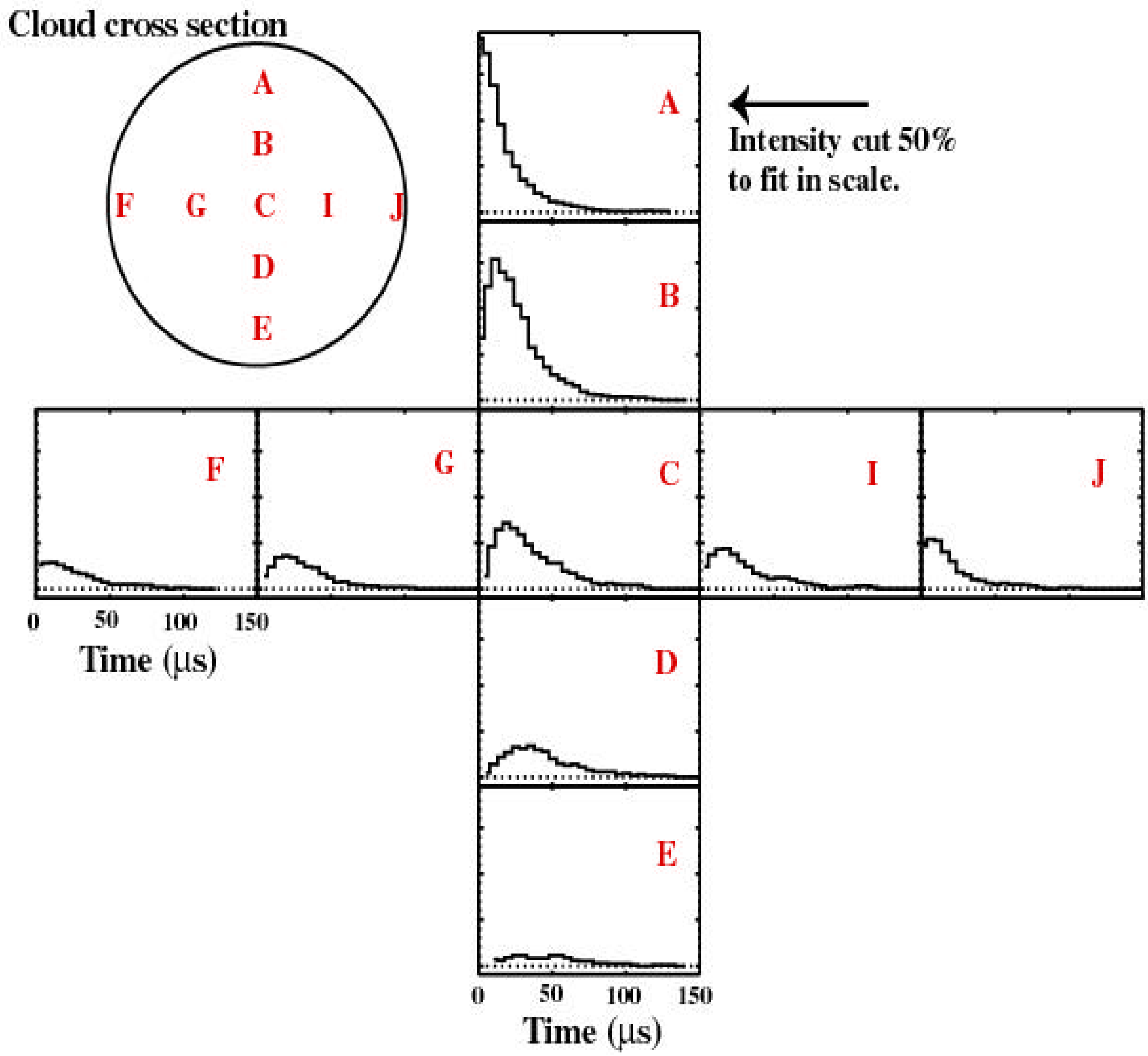
(A) These panels show the density of photons falling on the sky in the case of a pulse occurring near the top, center, and bottom of a spherical cloud. The distributions are shown (blue) as functions of x,y position on the sky. The histograms show the azimuthally averaged distributions of photons, as a function of the angle they make with zenith (i.e., 0^o indicates the number of photons landing directly over the cloud). Note that all distributions shown have been normalized to what would be expected in the case that there were no cloud present.

(B) The cross depicts the time-traces seen by a detector located directly above the cloud for the cases where the pulse occurs at each positions within the cloud as shown in the circle. Note that there is a factor of almost 40 difference in the peak intensity seen when the cloud goes off near the top as opposed to near the bottom of the cloud (positions A and E), whereas the horizontal placement of the event matters comparatively little.

(2A)


Photon density on whole sky over cloud
Zenith angle distribution of photons on sky
4
3
2
1
0
0
33
66
100
Event occurs near top of cloud: photons scatter preferentially towards zenith.
Y position -->
1.0
0.8
0.6
0.4
0.2
0
0
33
66
100
1 same number of photons scattered into a given zenith angle as is expected in the limit of nocloud.
X position -->
0.6
0.4
0.2
0
0
33
66
100
Event occurs near bottom of cloud: photons scatter preferentially towards horizon.

(2B)


Cloud cross section
A
B
F G C I J
D
E
A
Intensity cut 50% to fit in scale.
B
F
G
C
I
J
0 50 100 150
Time (μs)
D
E
0 50 100 150
Time (μs)

Results

3. Cloud Shape

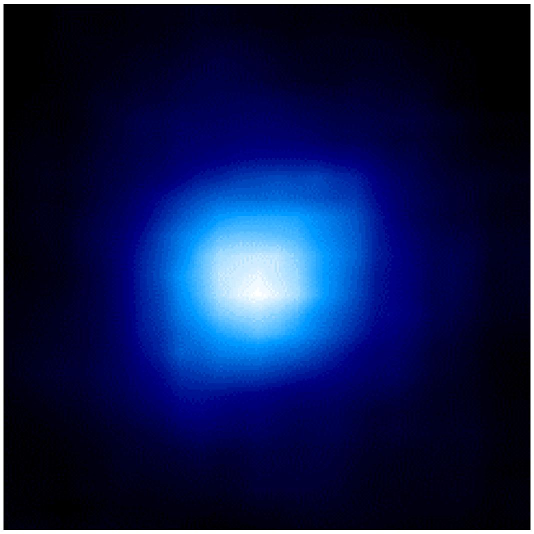
While cubical clouds ultimately scatter photons isotropically, as do spherical clouds, any cloud shape with axial ratios other than unity will scatter photons preferentially into different distributions on the sky, because in certain directions there will simply be less cloud for the photons to pass through, and therefore less net deflection along certain paths than along others. Thus cylindrical and planar clouds redirect photons anisotropically as shown in the panels to the left.

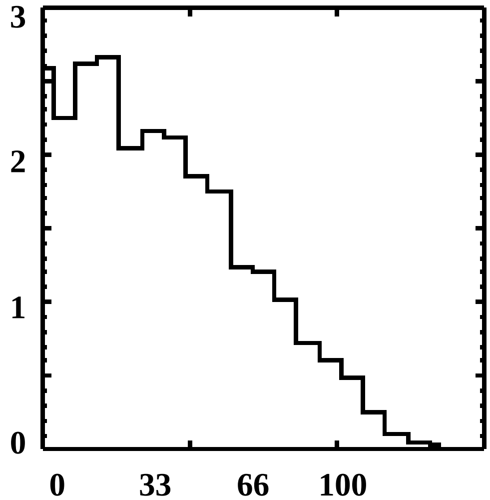
In this case, "planar" means a cloud of infinite extent in the x and y directions, and having thickness z in altitude. Photons directed parallel to the plane Will never escape that way (to the horizon) and ultimately will be sent either towards the ground or towards zenith. As a result, an event occurring within a planar cloud will appear brighter when viewed from directly above than if it were observed elsewhere; also, those photons reaching the zenith will have been on average delayed quite a bit, in that they traverse the plane for some time before being redirected. These horizontally extended clouds therefore give rise to wave forms with extended tails, whereas spherical clouds yield wave forms with a more abrupt cutoff.

Photon density on whole sky over cloud

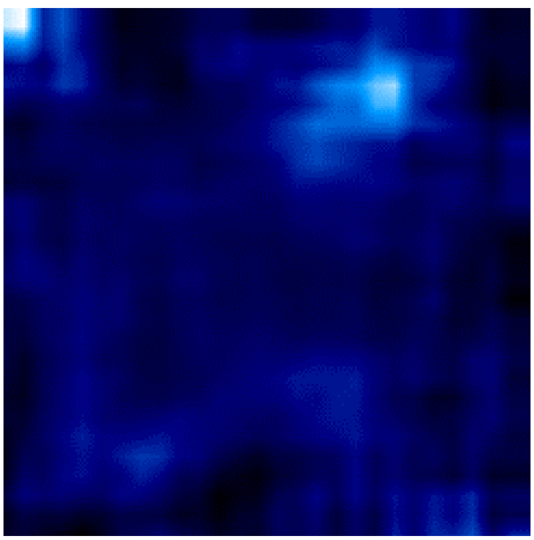
Zenith angle distribution of photons on sky

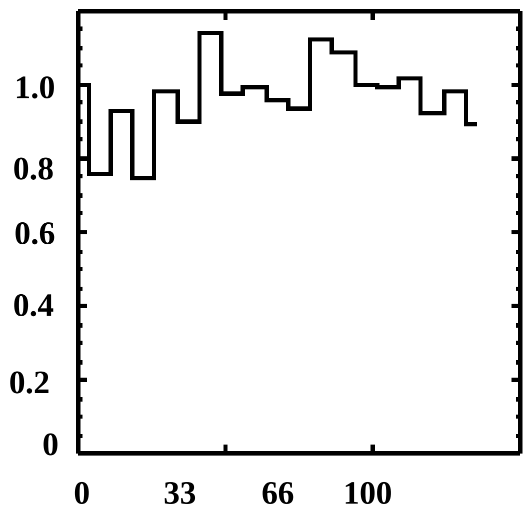
(3)



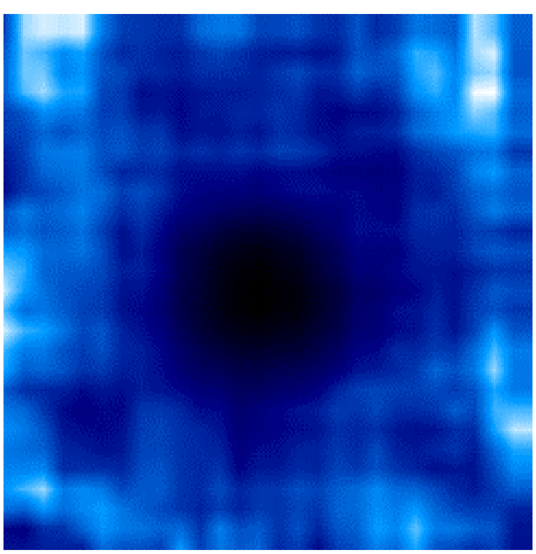


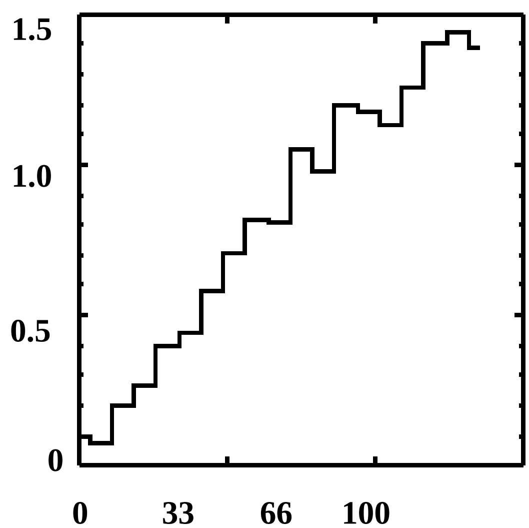
Planar cloud: Photons cannot escape towards horizon and are therefore eventually sent back towards zenith.





Cubic cloud: Very similar to spherical and no-cloud case distributions, i.e., net isotropic scattering.





Cylindrical cloud: Skinny cylinder allows photons to escape more readily towards the horizon.

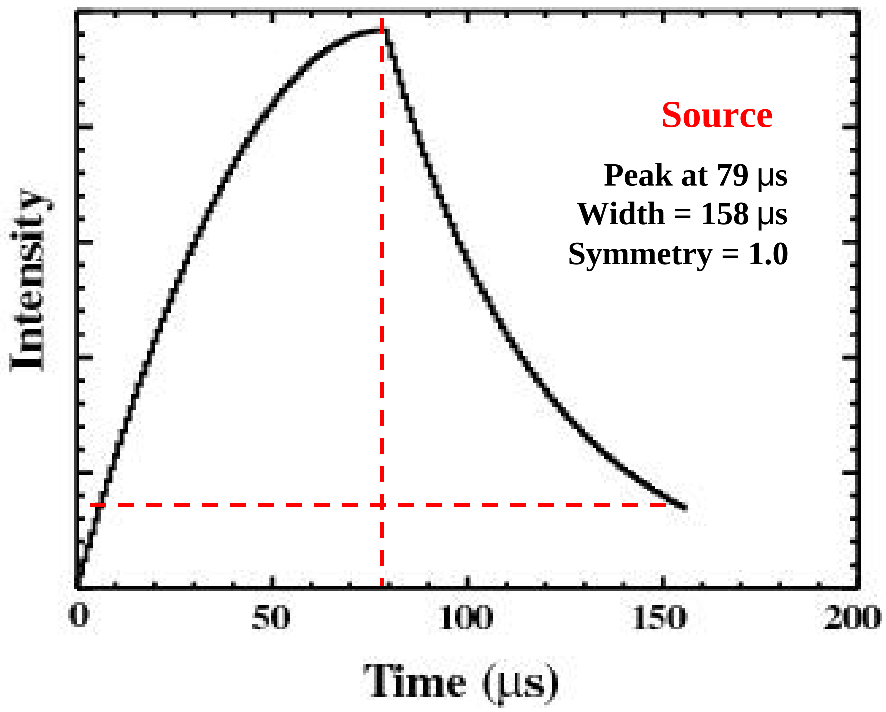
Results

4. Temporally Extended Sources

Here we approximate temporally extended sourceby superimposing the results from delta-function sources.

(A) The source function we used is Typical for lightning return strokes *(Guo & Krider 1982)*. Note that in the limit of no cloud, the output signal becomes this input signal, and hence in this case the width would be twice the delay.

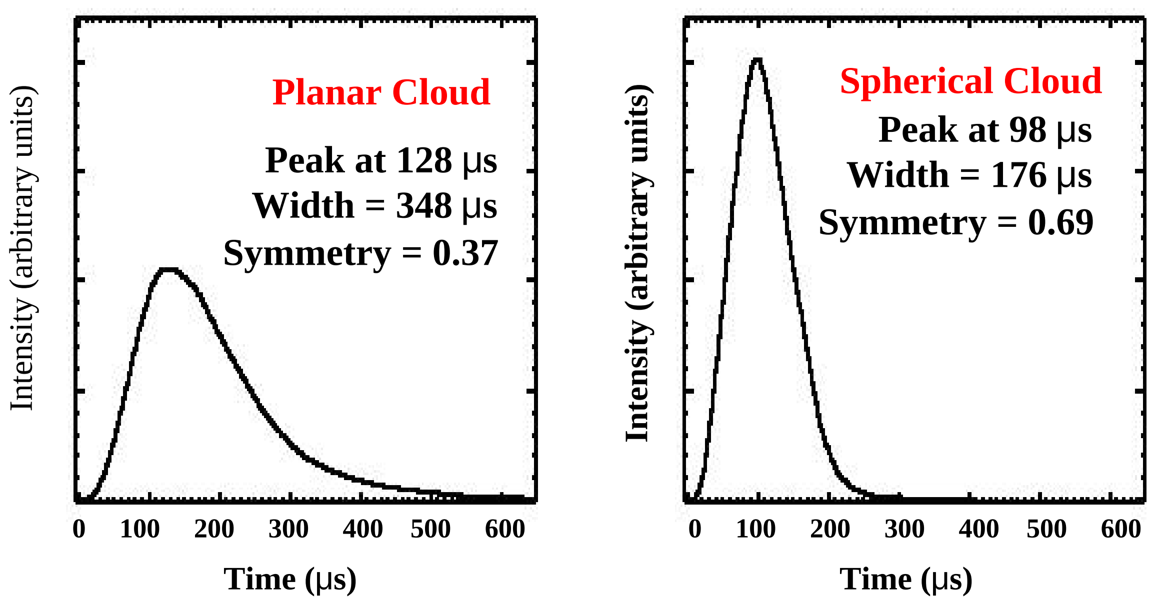
(B) Having created a source lasting for 158 μs in the center of a spherical cloud, we can see a pronounced effect due to the cloud geometry. As noted in 3. above, the horizontally extended clouds cause a greater delay in a photon escaping a cloud.



Source
Peak at 79 μs
Width = 158 μs
Symmetry = 1.0
Intensity
0
50
100
150
200
Time (μs)

(4A)

(4B)



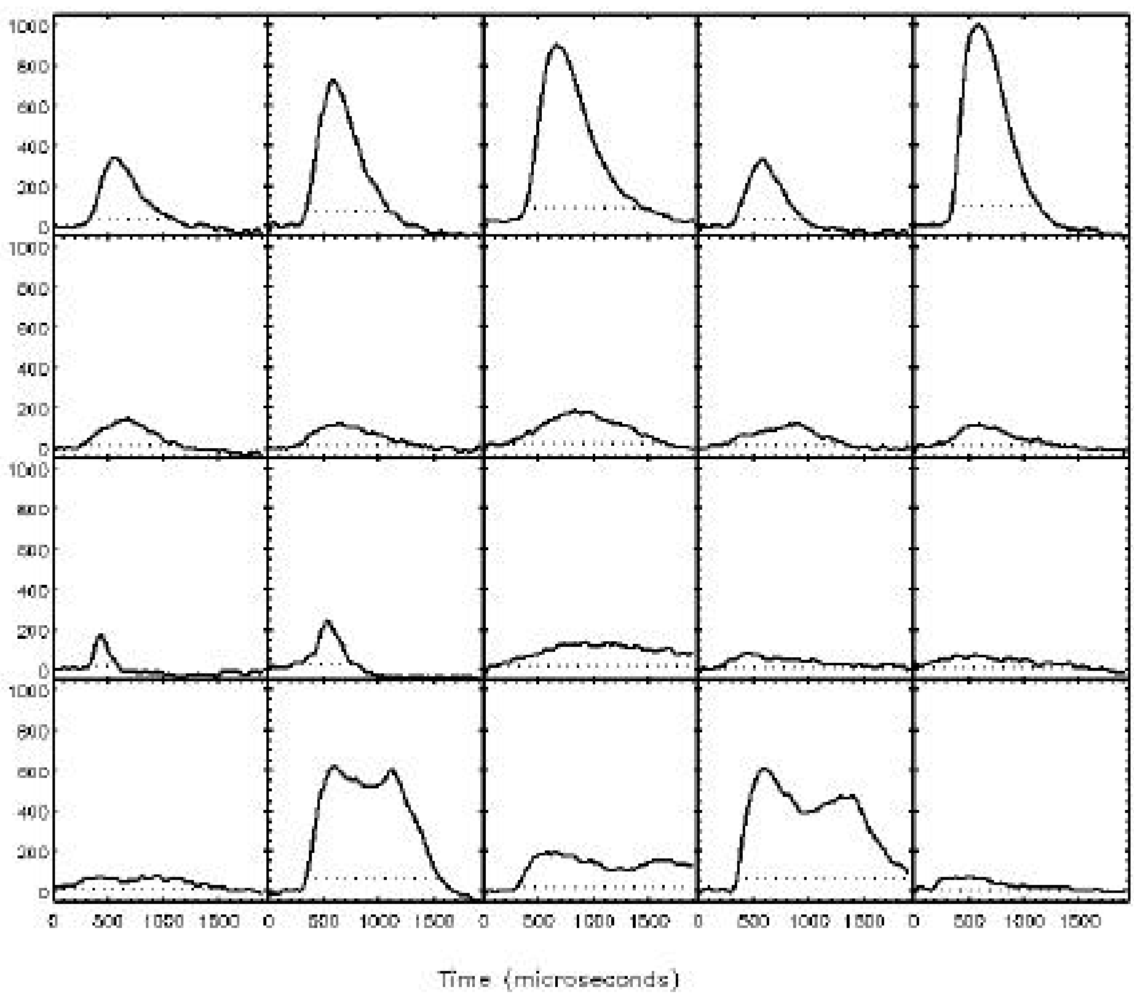
Planar Cloud
Peak at 128 μs
Width = 348 μs
Symmetry = 0.37
Intensity (arbitrary units)
0
100
200
300
400
500
600
Time (μs)
Spherical Cloud
Peak at 98 μs
Width = 176 μs
Symmetry = 0.69
Intensity (arbitrary units)
0
100
200
300
400
500
600
Time (μs)

Comparison with data

The FORTE satellite, built by Los Alamos and Sandia Labs and launched in 1997, carries two optical lightning detectors, including a silicon photodiode detector (PDD), sensitive from 0.4 to 1.1 μm, which records a time-trace of events occurring within the satellite's 1200 km (80°) field-of-view. Records typically cover 1.92ms with 15μs resolution. Data collected to date reveal a wide variety of intensities, shapes and structures. The goal of this modeling effort is to understand the differences in discharges and cloud environments which give rise to this variety.

Note: vertical axis has uniform scale. Notice the wide range of trace widths and strengths, as well as the variety in line shape and structure. This is not, however, a sample which accurately reflects the relative frequency with which each profile shape occurs; those along the top row occur more often than others.

Sample of PDD wave forms



Comparison with data

Signal Delay

• We use the RF signature from lightning, measured by the FORTE satellite, as a time fiducial, in order to estimate the delay of the optical signal (measured by the FORTE PDD) due to scattering by clouds.

• There is some natural delay between the RF emission and the optical emission; it is the time necessary for current to propagate up the channel, after the return stroke, back into the cloud, where the optical emission will occur. This delay is ~50 → 100 μs.

• Thus we can estimate the contribution to the observed RF-optical delay which is from scattering:

$$\Delta t_{rf\text{-}pdd} = \Delta t_{emission} + \Delta t_{scatter}$$

• PDD statistics find that $\Delta t_{rf\text{-}pdd}$ = 243 → 380 μs, depending on the type of lightning considered. (*Suszcynsky et al. 1999, in press JGR; Kirkland et al. 1998, LANL report LA-UR-98-4098*)

• We therefore can assume that $\Delta t_{scatter}$ ~ 140 → 190 μs for return strokes. (We don't have a very good idea of $\Delta t_{emission}$ for other types of lightning, and therefore cannot estimate $\Delta t_{scatter}$ from $\Delta t_{rf\text{-}pdd}$.)

Comparison with data

Signal Broadening

• Guo & Krider (1982) estimate that the optical source duration is approximately W_{source} ~ 158 ± 33 μs for return strokes.

• The FORTE PDD data show s a large range of output signal widths,

$$W_{obs} \sim 200 \rightarrow 1300\ \mu s$$

• Thus we estimate that scattering broadens the signal by

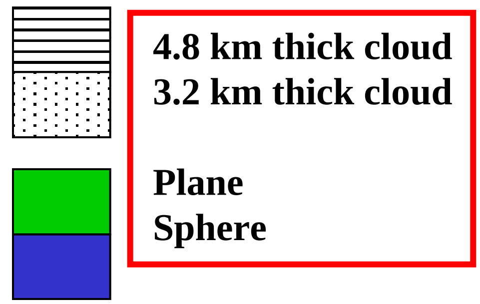
$$\Delta W \sim 0 \rightarrow 1200\ \mu s.$$

Obviously both the delay and broadening of the lightning signature will be more pronounced for more optically thick clouds.

We have run our simulations with a range of cloud sizes, shapes and optical depths (densities) in order to approximate the full range of real cloud types, and have found ranges of delay and broadening values which correspond to these observed values.

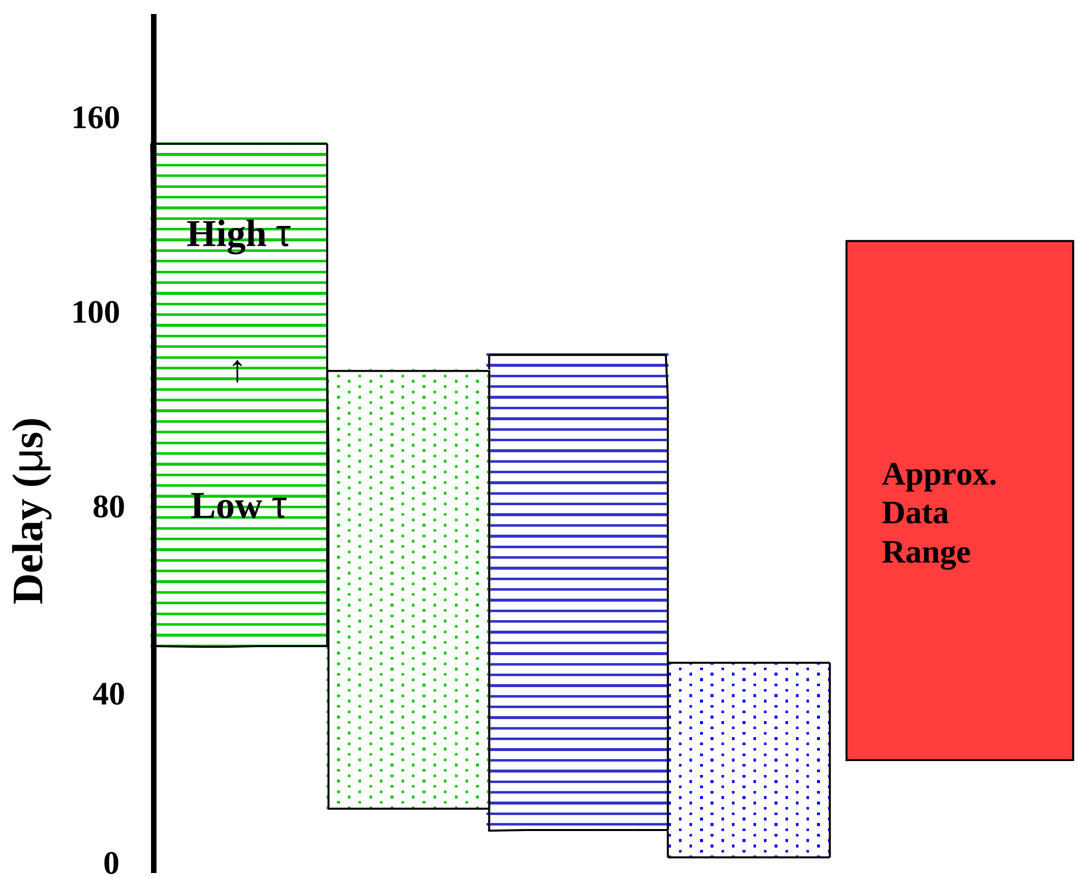
Comparison with data

Using the results from section 4, and varying the cloud size, shape and optical depth, we find ranges of possible values for the delay and broadening of the source signal due to scattering by intervening clouds. These ranges agree with values seen with the FORTE satellite studies of lightning.

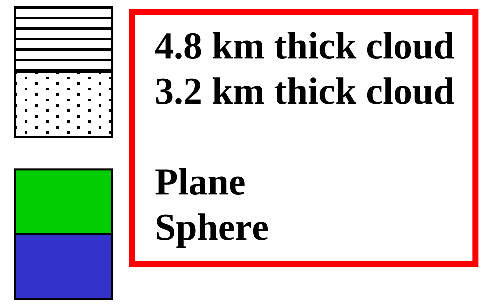


Signal Delay

Range of delay due to scattering (μs), from simulations with varying cloud characteristics.

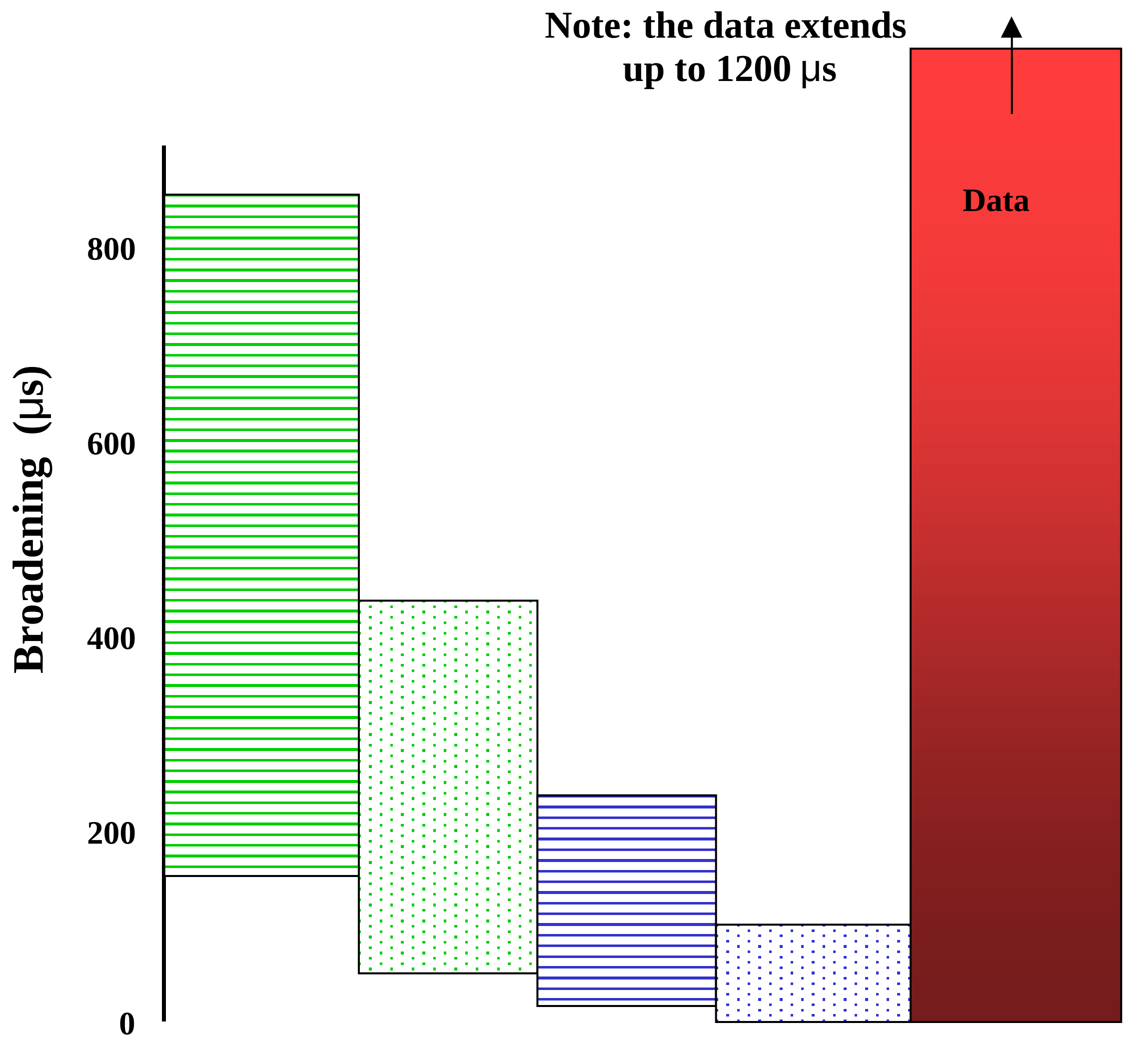


Comparison with data



Signal Broadening

Range of signal broadening due to scattering (μs), from simulations with varying cloud characteristics.



Note: the data range is simply bounded by extreme upper and lower limits; the true range is likely to be a subset of this estimate.

Conclusions

• An optical pulse viewed through a cloud of scattering particles will be attenuated as light is scattered out of the incident beam.
• Losses due to absorption of the light are very small and account for less than 10% of the total attenuation.
• In a small-ish cloud with optical depth of only τ ~ 200, there is a factor of ~40 greater loss when the event occurs near the bottom of the cloud, compared to when the event occurs near the top of the cloud. The observable effects of scattering scale linearly with both cloud size and optical depth, and therefore for realistic thunderclouds there can be more than an order of magnitude variation in observed peak event intensity simply by virtue of the event's placement within a cloud.

• A horizontally truncated cloud will scatter light out its sides, towards the horizon. A horizontally extended cloud, however, will ultimately re-direct the photons either to zenith or into the ground, resulting in an enhanced observed brightness when the cloud is viewed from directly above or below.
• Those photons which would otherwise be lost to the horizon, however, arrive at the zenith much later, and as a result the time series waveform of events within extended clouds show lower peak amplitudes and long tails, whereas events within smaller, finite clouds appear stronger and have more abrupt cutoffs. That is, different cloud geometries scatter the photons into different distributions on the sky, such that the combination of cloud shape and viewing angle is as important a determinant of apparent event intensity as is the cloud optical depth.

• Even the simple cases considered here yield good agreement with the values for scattering delay and broadening found in the FORTE/PDD data.
• The smallest observed profile widths in the FORTE data are ≤ 200 μs. Our results suggest that these signals have been broadened very little if at all by intervening cloud, and that the cloud must be small and of low optical depth. These events are often seen to have larger than average peak brightnesses; *Kirkland (1999, LANL report LA-UR-99-1685)* describes them as possibly being due to the satellite enjoying an unobstructed line of sight to the event, in agreement with the results of these simulations.
• Conversely, the data include events which are delayed, presumably by scattering, by up to 100 μs or more. Such events are only accounted for in the simulations by clouds of considerable horizontal extent. Thus the approximation of an infinite plane parallel cloud is in fact appropriate in some percentage of cases.

Future Work

• In order to make the results of this study directly applicable to understanding the FORTE/PDD data, we must transform the percentage transmissions into detection probabilities as a function of zenith angle, event amplitude and event/storm type.

• In order to make the model scenarios more realistic, we are currently working to incorporate non-uniform particle density distributions within the clouds. Realistic clouds have a density structure that varies with altitude. It is therefore possible that the detection probability similarly varies with the event altitude (and therefore event type) in some way other than that seen in our current results. Also, realistic clouds have some ice fraction in them, and currently we have ignored ice entirely.

• We are also currently beginning to consider "imperfect" cloud shapes. These will include features such as rough cloud surfaces and folds or layering within the clouds. Roughened surfaces, for example, might make the distribution of throughput photons more isotropic, regardless of cloud shape.

• We can also perform a simple experiment using available weather/storm data, from the NEXRAD systemfor example, alongside the FORTE/PDD data to explore the cloud shape effect on pulse broadening. Oursimulations indicate that large scale storm systems should substantially widen the observed pulse; by studying PDD data on a storm-by-storm basis, we hope to see if this is an observable effect.

Acknowledgements

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